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# JAERI-KEK Joint Project on High Intensity Proton Accelerators

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Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Organization (KEK) are promoting the joint project integrating both the Neutron Science Project (NSP) of JAERI and the Japan Hadron Facility Project (JHF) of KEK for comprehensive studies on basic science and technology using high-intensity proton accelerator.

This paper describes the joint project prepared by the Joint Project Team of JAERI and KEK to construct accelerators and research facilities necessary both for the NSP and the JHF at the site of JAERI Tokai Establishment.

***KEYWORDS: Joint Project, High-Intensity Proton Accelerator, Spallation Neutron Source, Particle Physics, Nuclear Physics, Hadron, Neutrino, Neutron Science, Structural Biology, Material Science, Muon Science, Exotic Nuclear Beams, Nuclear Waste Treatment***

## I. Overview of the Joint Project

### 1. The Highest Beam Power in the World

This paper describes a new proposal to pursue frontier science in particle physics, nuclear physics, materials science, life science, and nuclear technology, using a new proton accelerator complex at the highest beam power in the world. The plan has been discussed and it is proposed jointly by the High Energy Accelerator Research Organization (KEK) under the Ministry of Education, Science, Sports and Culture (Monbusho) and the Japan Atomic Energy Research Institution (JAERI) under the Science and Technology Agency (STA). Previously, these institutions proposed the Japan Hadron Facility (JHF) at KEK and the Neutron Science Project (NSP) at JAERI, respectively. The present new joint plan, temporarily called the "Joint Project", is based on these two past proposals. It is also proposed that accelerators of this Joint Project be constructed at the JAERI site.

The frontiers of accelerator science are in two complimentary directions. One path is towards the highest beam energy, examples for which are LEP (electron + positron collider at 100 GeV each), RHIC (Au + Au collider at 100 GeV per nucleon each), and LHC (proton + antiproton collider at 7 TeV each). The major purpose of these energy-frontier accelerators is to hunt for new particles, for example, in particle physics. The other path is towards the highest beam power. Many new accelerators are based on this philosophy, such as high-intensity electron accelerators that provide intense synchrotron radiation sources. In proton accelerators, the high beam power allows production of a variety of intense secondary particle beams such as kaons, neutrons, muons, neutrinos, antiprotons, and short-lived radioactive nuclear beams. In nuclear and particle physics, an example using these secondary beams is to measure rare processes such as neutrino oscillations and CP violation. In addition, sciences and technologies other than particle and nuclear physics can be carried out by using these secondary beams. These sciences and technologies include a) materials and life sciences with neutron and muon beams, b) accelerator-driven nuclear transmutation of long-lived nuclides in nuclear waste, and c) astrophysics research using radioactive isotope beams. The present proposal represents a major step in the direction of the intensity frontier.

### 2. Accelerators and Science in the Joint Project

In the present chapter a flavor of these programs together with the accelerator configuration are described.

The proposal has two phases. The "Phase 1" accelerator complex consists of

1. 400-MeV normal-conducting Linac,
2. 600-MeV Linac (superconducting) to increase the energy from 400 to 600 MeV,
3. 3-GeV synchrotron ring, which provides proton beams at 330 μA (1 MW), and
4. 50-GeV synchrotron ring, which provides proton beams at 15 μA (0.75 MW).

In addition, an upgrade towards 5-MW proton beam power at the few GeV energy region is proposed as a "Phase 2" project of the present proposal. The final decision on the selection of the accelerator type in the "Phase 2" will be made after obtaining performance data at the Phase 1 accelerator. **Figure 1** shows the basic configuration of the proposed "Phase 1" accelerator complex.

At the initial stage, the normal conducting 400 MeV Linac will be used as an injector to the 3-GeV ring. At the stage when the superconducting 600 MeV Linac becomes stable, however, this 600-MeV Linac will be switched as the injector to the 3 GeV ring.

At the 50-GeV Proton Synchrotron (PS) nuclear/particle physics experiments using kaon beams, antiproton beams, hyperon beams and primary proton beams are planned. Using kaon beams, production of strangeness in nuclear matter become possible, and the study of the influence of nuclear matter on this impurity probe of a strange particle will be performed. Experiments on kaon rare decays to measure CP matrix elements, an experiment on neutrino oscillationusing the Super-

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Kamiokande as a detector, etc. will also be carried out.

The 3-GeV ring will be used as a booster synchrotron for the 50-GeV main ring. In addition, it is designed to provide beam power of 1 MW. Extensive physics programs which cover nuclear/particle physics, condensed matter physics, materials sciences and structural biology will be carried out there. Among them the major highlights are materials sciences and structural biology using neutrons produced in proton+nucleus spallation reactions. Since a neutron has a magnetic moment but no electric charge, neutrons can be used for the study of magnetic properties of matter. Also, since the neutron has a mass which is similar to that of the hydrogen atom, neutrons can probe sensitively the location and dynamic behavior of hydrogen atoms in materials. The role of hydrogen atoms in biological cells is of particular interest in life science and, there, the neutron beams play a crucial role for these studies. In addition to neutrons, muon beams are also important in which μSR (muon spin rotation/relaxation), muon catalyzed fusion, and other materials sciences can be conducted. Also, particle-physics experiments such as a $\mu N \rightarrow eN$ conversion experiment can be performed. Radioactive beams produced from the 3-GeV PS are also useful to nuclear/astro physics research. Finally, the high-current 600-MeV Linac will be used for R&D for the accelerator-driven nuclear transmutation.

The beam power is sufficiently high for all the above sciences. However, a higher beam power will enrich, in particular, neutron sciences. Thus, we plan in Phase 2 to upgrade the accelerator to 5 MW for spallation neutrons.

### 3. International Responsibility

In the 21st Century it is extremely important for Japan to play a major leadership role in accelerator science in the world. The present Joint Project is desired in the world's science community for many reasons. For example, the OECD Mega Science Forum for neutron sources recommended the construction of advanced neutron sources in each of the three regions: Asia/Pacific rim, Europe and North America. North America recently started the SNS Project, aiming at a 4-MW proton accelerator. In Europe a project called the ESS for 5 MW is under discussion, to follow the 0.16-MW ISIS neutron source.

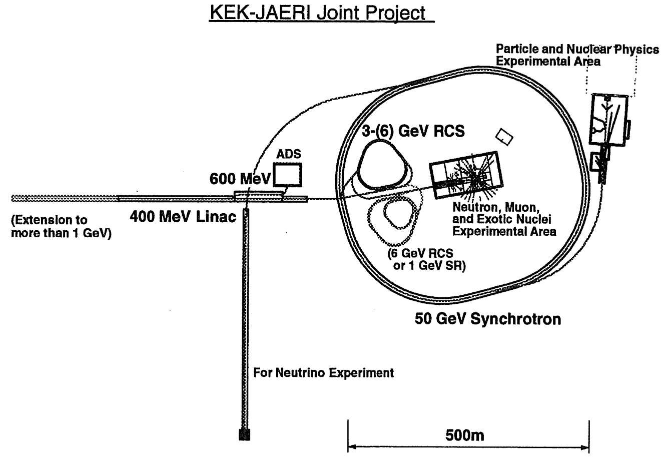


**Fig. 1** Layout of the accelerator complex of the Joint Project. The facilities with parentheses are for the future upgrade.

The present Joint Project is comparable to these two future projects and, if constructed, it will be one of three major centers in the world for neutron sciences.

The OECD Mega Science Forum for nuclear physics also emphasized the scientific importance of the JHF proposed in Japan and urged the international communities and foundations to form partnerships to take advantage of this future facility. Here, the present Joint Project becomes, if constructed, the world center for hadron physics and many international users from Europe, America, and Asia will come to Japan to do experiments.

Interests in the accelerator-driven system (ADS) for transmutation of long-lived nuclides has grown in recent years in many countries as a possible means to improve the management of high-level radioactive waste. The OECD Nuclear Energy Agency will start the Partitioning and Transmutation System Study, Phase 2: Comparative Study of ADS and Fast Reactor in Advanced Fuel Cycles. The facility for ADS experiments under the present Joint Project provides, if constructed, opportunities for foreign countries interested in the ADS to conduct experiments jointly.

In addition, the role of Japan in the Asian countries and the Japanese relation to these countries is an important issue. Since the present Joint Project will attract Asian scientists, the project team will pay special attention to make it easier for Asian and Pacific countries to participate in this project.

### 4. Site Selection

The site of the proposed accelerators is chosen to be the JAERI Tokai site. Since the ultimate goal of this proposal is to seek 5 MW beam power including R&D experiments for accelerator-driven transmutation, radioactive waste disposal of the spallation target and the use of nuclear fuel materials for transmutation are the most important issue in the process of our site selection. For accelerators up to 1-MW beam power both KEK-Tsukuba and JAERI-Tokai can handle them at an almost equal level of effort. On the other hand, for the accelerators at 5 MW the handling of the radioactive waste and the use of nuclear fuel materials for transmutation experiments are by far easier at the JAERI-Tokai site, since JAERI-Tokai is the place where several research reactors, nuclear-waste handling facilities and other related facilities are operated.

## II Research Facilities and Programs

### 1. Particle and Nuclear Physics

Some of the ways to develop an understanding of particle and nuclear physics are to do precision studies, to investigate exotic systems, or to look for unseen phenomena. These studies are only possible when beams of very high intensity are available. The 50-GeV PS will provide a beam current of 15.6 mA at its initial stage to enable these important particle and nuclear physics experiments with high-intensity primary and secondary beams. **Figure 2** shows a preliminary layout of the experimental area of the 50-GeV PS. Here, the primary beams are protons (unpolarized and polarized later) as well as heavy-ions at a later stage, and the secondary beams include π's, K's, hyperons, neutrinos, muons, and antiprotons. These secondary

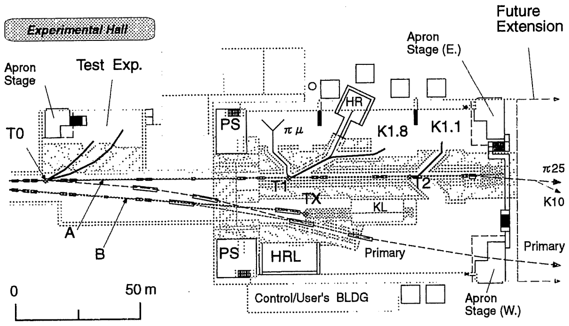


**Fig. 2** Cutaway view of the neutron scattering experimental facility

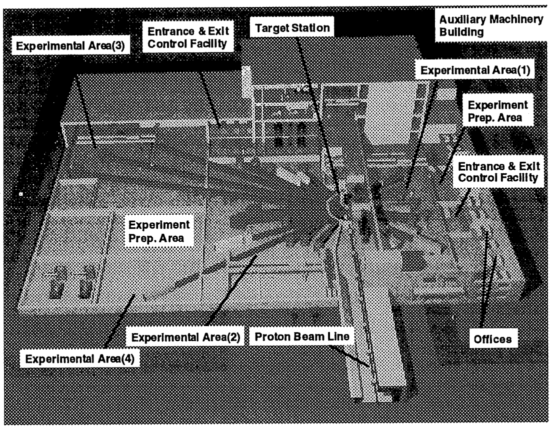


**Fig. 3** Cutaway view of the neutron scattering experimental facility

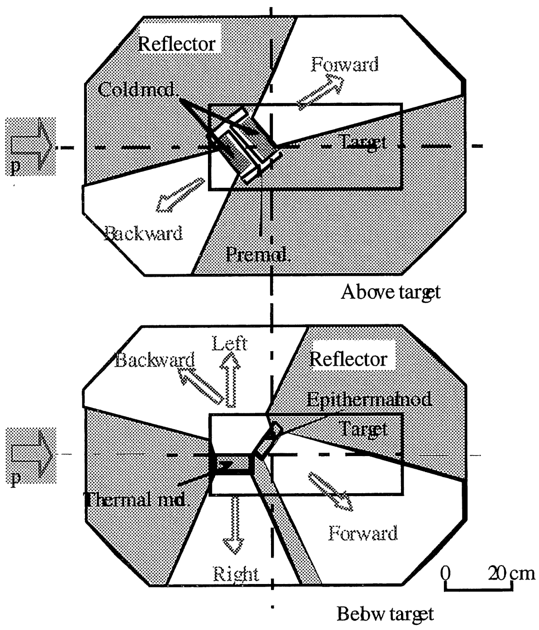


**Fig. 4** Configuration of moderators

beams will have the highest intensity in the world in this energy domain.

Physics programs at the 50-GeV PS cover a broad range of topics in particle and nuclear physics . Topics mentioned herein are not complete, since more detailed reports are available[1].

## 2. Neutron Science

The neutron is, in many ways, one of ideal probes for the study of condensed matter, and neutrons have made a pivotal contribution to a wide variety of science and technology.

Japan pioneered an accelerator-based neutron source at Tohoku University in the middle 1960's, built the first user-oriented spallation source (KENS) in 1980 at KEK, and started the international collaboration between KEK and ISIS. In 1987, KEK proposed a 0.6-MW (upgradable to 1.2 MW) PSNS facility (N-arena)[2] as a part of the JHF project. On the reactor side, the JAERI research reactors have developed a large user group for neutrons since 1960. The upgrade reactor JRR-3M with cold neutron source was built in 1990, and the requirement of a new facility has been growing up. In 1994, JAERI proposed the 5-MW PSNS facility[3] as a part of the Neutron Science Project. Those two proposals of PSNS have been merged to the current project.

The field in which the most prominent development is expected by the high-flux neutron is structural biology. The positions of hydrogen and hydration in proteins, DNA and physiologically important materials will be routinely determined and the physiological function will be investigated by inelastic neutron scattering. Soft matter, such as polymers, liquid crystals and colloids, forms complex systems and receives much attention from the fundamental science, as well as from the application, point of view. The use of neutrons for industrial applications is also important. The high-flux would make possible characterizations of new materials in a multi-parameter space, such as concentrations, temperatures, pressures and so on. Neutron beams can also be used to image the interior structure of bulk materials by neutron radiography. The non-destructive characterization of various materials will help to detect flaws that could result in failures. The neutron is also an important neutral particle to study fundamental properties of nature.

Extrapolating from the success of the existing PSNS, we are certain that there will be breakthroughs in many scientific and engineering fields, once we build the 5-MW JSNS which has considerably higher peak and time-averaged neutron flux than the current ones.

**Figure 3** shows the birds-eye view of the conceptual layout of the neutron experimental hall after the completion of the 5 MW upgrade [2,4,5] . We adopted a horizontal proton-beam injection scheme, and the target-maintenance facilities at the opposite side of the proton beam line.

The target-moderator-reflector arrangement has been optimized for the 5-MW stage to realize highest performance for extraction of neutrons with respect to brightness and sharp-time structure as well as for technical feasibility, as shown in **Fig. 4**.

We selected two identical coupled super-critical hydrogen moderators with a newly proposed fully extended premoderator to provide high-intensity/high-resolution cold neutrons, one decoupled hydrogen moderator to provide high-resolution thermal neutrons and one decoupled room-temperature $H_2O$ moderator for high-resolution epithermal neutrons.

Technical issues of the target system are being clarified through the design work focused on the 5MW operation, which can be divided into the following three groups: (1) the structural integrity against the thermal shock, the pressure wave and the high heat density which are caused by the pulsed proton beam, and the degradation of material strength by irradiation etc., (2) the safety performance to prevent the off-normal occurrence such as a mercury or a coolant ingression to the surroundings from the containers, and (3) the maintainability which will likely be ensured by using remote handling devices.

In order to solve these issues, R&D work as well as design work including thermal-hydraulic and structural strength analysis are being vigorously carried out.

With R&D activities, the present concept for the mercury and the solid targets are expected to be sustainable for a 1MW operation, hopefully up to 2MW. For a 5MW operation further R&D efforts will be devoted.

## 3. Muon Science

Muons can be used in various fields of scientific research including: (1) fundamental muon physics, such as precise measurements of particle properties of muons, hunting for rare decays, etc.; (2) muon catalyzed fusion and its application to energy resource problems; (3) use of the muon as a spin probe sensitive to the microscopic magnetic properties of various new materials; and (4) non-destructive element analysis to be applied to bio-medical studies, etc.

The facilities for Muon Science are mainly aimed at the production of pulsed muons, which will be generated by 3-GeV protons. Design work on the advanced muon channel is in progress with the aim of producing beams which are not only the most intense so far, but also the highest in quality. The proposed layout of the facility for Muon Science to be placed between the facilities of Exotic Nuclei and Neutron Science with two thin targets (10mm -20 mm) is shown in **Fig. 5**.

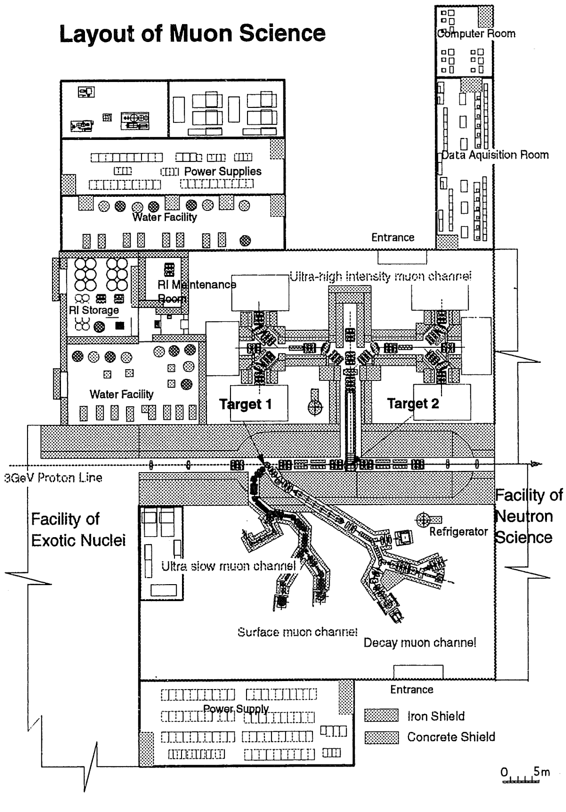


**Fig. 5** Proposed facility layout of the Muon Science

## 4. Science with Exotic Nuclear Beams

The aim of this facility is to open up new research fields in nuclear physics and chemistry, study of fundamental interactions through β-decays, nuclear astrophysics as well as multidisciplinary fields of science by means of radioactive nuclear beams (RNB).

**Figure 6** shows a schematic layout of the proposed facility at the 3 GeV PS. Various exotic nuclear species, produced by 3 GeV protons via spallation, multi-fragmentation or fission of a proper target and mass-separated through the isotope separator on-line (ISOL), are accelerated in heavy-ion linacs. The beams from the ISOL and all the linacs can be transported simultaneously to different experimental stations by using pulsed bending magnets.

Nuclear reactions induced by RNB become possible for all kinds of targets in the proposed facility and provide new powerful tools for studying reaction mechanism and spectroscopy of exotic nuclei such as superheavy elements and R-path nuclei as well as astrophysical reaction rates induced by unstable nuclei. In combining the RNB facility with the muon or spallation-neutron-source facility of the present project, possibilities of studying muonic atoms with exotic nuclei or neutron-capture by unstable nuclei will open for the first time in the world.

## 5. Nuclear Waste Transmutation

One of the most important problems with nuclear energy is the management of high-level radioactive waste (HLW) arising from the reprocessing of spent nuclear fuels. The major candidate scheme for the long-term waste management in most nuclear countries is the permanent disposal of unpartitioned HLWs into a deep underground repository. There is, however,

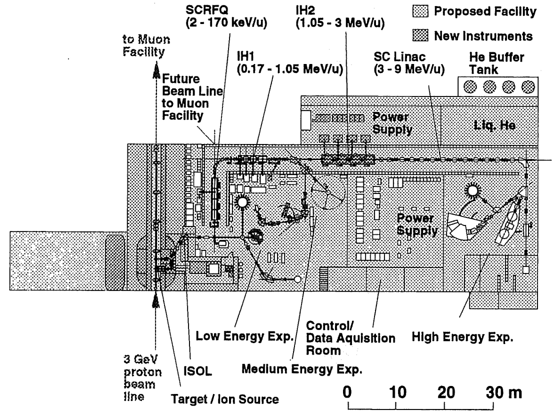


**Fig. 6** Plan view of the proposed facility

considerable attention directed toward the further reduction in the long-term potential hazard by partitioning and transmutation (P-T). The objectives of P-T are to reduce long-lived nuclides in HLW.

There are two concepts of fuel-cycle scenarios involving P-T. One is an advanced fuel-cycle concept, where commercial fast breeder reactors are used for transmutation(6). Another is the JAERI's concept of double-strata fuel cycle, which consists of a P-T fuel cycle (the second stratum) separated completely from the conventional fuel cycle for commercial power reactors (the first stratum). Dedicated systems specially designed for transmutation purpose could be introduced in the P-T fuel cycle.

A dedicated transmutation system can be either a critical system (burner reactor) or a subcritical system (ADS). For ADS, its subcriticality mitigates the problems and allows the maximum transmutation rate. The other advantage of ADS is the flexibility of designing owing to the fact that the system does not need the criticality condition. For this reason, ADS could be an optimum device for transmutation.

Conceptual design studies have been carried out for accelerator-driven transmutation systems(7). For the present, the lead-bismuth cooled option is the primary candidate for the accelerator-driven transmutation system. In ADS, lead-bismuth can play roles of both coolant and spallation target material. A conceptual drawing of the lead-bismuth cooled ADS plant is shown in **Fig. 7**.

The major areas of technology to be tested and demonstrated will be subcritical reactor physics, system operation and control, transmutation, thermal-hydraulics, and material irradiation.

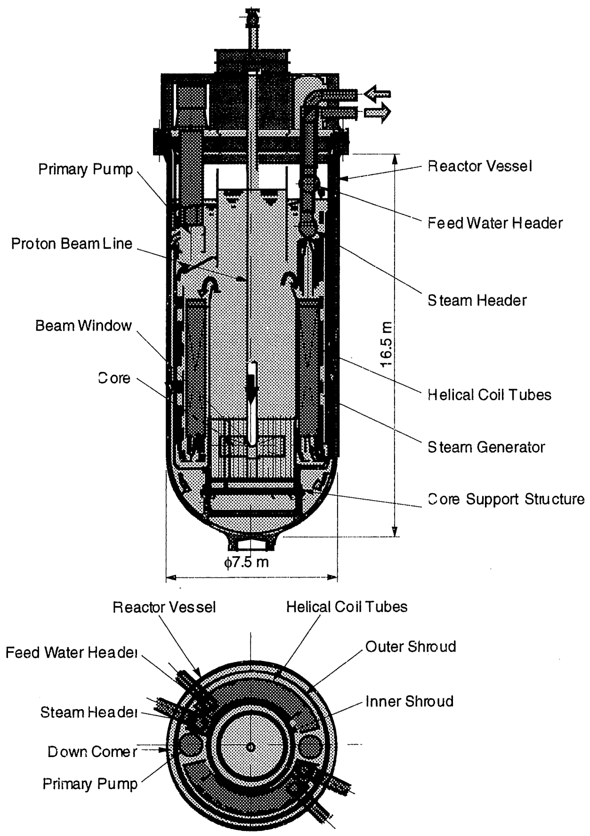


**Fig. 7** Concept of Pb-Bi cooled accelerator-driven transmutation system

The first phase will be the subcritical reactor-physics experiments and fundamental demonstration of the feasibility of the ADS concept. It will demonstrate the sustained stable integral operation of a spallation target and a subcritical core driven by a proton beam at a low power level 10kWt.

Material irradiation test will be carried out the ADS engineering. The experimental system will be made up to a power level of around 2 MWt.

## III. Accelerator

### 1. Introduction

Higher proton intensity of several MW is more and more required for the development of various fields of science and engineering. This amount of beam power is, however, very difficult to achieve with the present state of the art of accelerator technology. Further experience in the construction, operation, and beam study of a machine newly designed on the basis of the present state of the art is indispensable for going much beyond a MW of proton beam power. The Joint Project is thus divided into two phases. Phase 1 is sufficient to promote various fields of science and engineering far beyond the present state. The empirical results will be fully utilized to go beyond 1-MW beam power up to Phase 2 including a several MW pulsed spallation neutron source. The required beam parameters for Phase 1 are listed in **Table 1**.

### 2. Accelerator Scheme

The 50-GeV main synchrotron requires a several-GeV injector in any case. A several-GeV rapid-cycling synchrotron (RCS) is significantly more advantageous over a several-GeV proton linac with regard to construction cost. The several-GeV RCS requires a several-hundred-MeV injector linac.

A pulsed spallation neutron beam with a pulse length of order 1 μs is much more useful than the longer-pulse or CW neutron beam. It is a reasonable choice to use the booster RCS to the 50-GeV synchrotron for producing the pulsed spallation neutrons.

The combination of the respective energies of 3 GeV and 400 MeV for the RCS and the linac is chosen by optimizing the costs for obtaining the 1-MW proton beam power.

For the accelerator-driven nuclear waste transmutation system (ADS), the proton beam with an energy of at least 600

**Table 1** Required Beam Parameters for the Phase 1 Accelerator

| | Energy | Current or power | pulse length | repetition |
|---|---|---|---|---|
| Nuclear and Particle Physics | 50 GeV | 15.6 μA | long and short pulse | high duty |
| Neutron Science | > 0.5 GeV | 1 MW | < 1 μs | ≤50 Hz |
| Nuclear Waste Transmutaion | ≥ 0.6 GeV | 0.05 MW | long pluse | high duty |

MeV is necessary with a long-pulse duration of order 1 ms. The beam from the 400-MeV normal-conducting (NC) linac will be injected to the superconducting (SC) linac, accelerated up to 600 MeV, and transported to the ADS experimental area.

The reasons why the 600-MeV beam is not injected to the RCS at the first stage will be discussed towards the end of Section 3.3.

The Joint Project accelerator complex in the Phase 1 thus comprises the 50-GeV main synchrotron, the 3-GeV RCS, the 400-MeV NC linac, and the 600-MeV SC linac. The first one provides a beam of 15.6 mA with a repetition rate of 0.3 Hz, while the second one provides a beam of 333 mA with a pulse length of a few hundred ns and a repetition rate of 25 Hz. The linac can provide a beam of 1.3 mA with a repetition rate of 50 Hz and with a pulse length of 500 ms (that is, a duty factor of 2.5 % and a peak beam current of 50 mA), if the linac beam is not chopped. The 50-GeV beam is slowly extracted to an experimental hall, where experiments are conducted concerning Kaon rare decay, hypernuclei, and others. The beam is also fast extracted to the neutrino oscillation beam line. The 1-MW beam of the 3-GeV RCS is fast extracted to an experimental area, in which three production targets, respectively, for pulsed spallation-neutron experiments, muon experiments, and exotic-nuclei experiments, are located in a series along one beam line. The 0.8-MW beam of the 600-MeV linac is used for the basic study of the ADS.

$H^-$ ions produced in a volume-production-type ion source with a repetition rate of 25 Hz, a pulse length of 500 μs, and a peak current of 53 mA, are accelerated up to 400 MeV by the NC linac. Then, the ions are injected to the RCS through a charge-exchange foil. Two buckets are thus filled out for 500 μs.

The fields in the quadrupole magnets and bending magnets are to oscillate sinusoidally with a rapid cycle of 25 Hz. The injection time of 500 μs is limited by the approximately flat bottom of the 25-Hz sinusoidal function. In each cycle the ring will accelerate $8 \times 10^{13}$ protons.

The two bunches thus accelerated are injected four times tothe 50-GeV synchrotron, in which eight bunches are accelerated ($3.2 \times 10^{14}$ ppp). After the 0.12-s injection the beam energy is ramped up to 50 GeV for 1.9 s, and then the beam will be extracted slowly during a time of 0.7 s. The ramping cycle is to be completed in 3.42 s, including the falling time of 0.7 s.

Since the Phase 1 accelerator complex has some parts common with the JHF accelerator design, one may refer to several reports on the extensive design study of the JHF accelerator for more detail[8-11].

## 3. Liniac

The scheme of the NC linac is shown in **Fig. 8**. The linac plays two roles; one is to inject the beam to the RCS, while the other is to provide beam directly to the ADS.

The design of the linac makes full use of knowledge obtained during the course of developing these linacs both at KEK and JAERI[12-23]. Up to the energy of 200 MeV the linac is essentially the same as designed for the 200-MeV linac of the JHF. KEK has already started the construction of the 60-MeV linac, including the RFQ linac, DTL, and the first two tanks of SDTL. This linac will be the low-energy front end of the Joint Projects. From 200MeV to 400MeV, a coupled-cavity linac (CCL) will be utilized[24-27]. The SC linac from 400MeV to 600MeV is based upon the development work by JAERI.

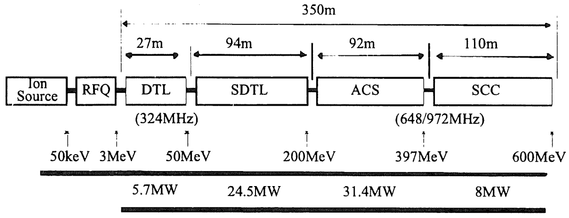


**Fig. 8** The scheme of the 600-MeV linac. A 20-m long matching section will be inserted between SDTL and ACS.

The design peak current of the RFQ for the original JHF is 30 mA, which is not enough for the 1-MW beam power. It is necessary to increase the beam current of the total accelerator system towards the design values, 50 mA, during the course of several years by continuing beam studies.

For the Phase 2 operation, the duty factor will also have to be increased. Various engineering problems such as efficient cooling of the accelerator structure and prevention of electric discharge will have to be solved by improving fabrication techniques and performing high-power tests.

From the viewpoint of the flexibility in the beam current, we should use quadrupole electromagnets in drift tubes for DTL rather than permanent quadrupole magnets (PQM). Since the frequency of the DTL should be as high as possible from the viewpoint of emittance-growth suppression, we chose the highest-possible frequency of 324 MHz, with which the quadrupole electromagnets can be contained in the drift tubes.

Another new feature of the linac is the use of a separated DTL (SDTL)after around 50 MeV. After the SDTL a CCL will be used with an acceleration frequency of 648 MHz or 972 MHz. The unique feature of the Joint Project linac is the use of SCCs for the high-energy linac above 400 MeV.

## 4. Lattice Design

### (1) 50 GeV Synchrotron

The main parameters of the 50-GeV synchrotron are listed in **Table 2**. Its lattice has been designed in order to meet the following requirements. First, one 100-m long straight section is necessary for slow extraction to the Particle and Nuclear Physics Experimental Hall. Second, the imaginary transition ($\gamma_T$), that is, negative-momentum compaction factor ($\alpha$), should be realized in order to make the ring free of the transition. Third, the phase advance has been chosen to be below 90° in order to avoid any strong resonance of the self space-charge force coupled with the beam-envelope modulation. Fourth, the maximum tunability is guaranteed.

### (2) 3 GeV Synchrotron

The main parameters of the 3-GeV synchrotron are listed in

**Table 2** Main parameters of the 50-GeV synchrotron.

| | |
|---|---|
| Beam Intensity | $3.2\times10^{14}$ ppp ( $8.2\times10^{14}$ ppp in future) |
| Repetition | 0.3 Hz |
| Average Beam Current | 15.6 mA (40 mA in future ) |
| Beam Power | 0.78 MW |
| Circumference | 1600 m |
| Magnetic Rigidity | 12.76 ~ 170 Tm |
| Lattice Cell Structure | 3-Cell DOFO×6 module + 4-Straight Cell |
| Typical Tune | (21.8, 16.3) |
| Momentum Compaction Factor | – 0.001 ( imaginary $\gamma_T$) |
| Total Number of Cells | 92 |
| The Number of Bending Magnets | 96 (6.75 m ) |
| Magnetic Field | 0.135 ~ 1.8 T |
| The Number of Quadrupoles | 184 (1.5 – 2 m) |
| Maximum Field Gradient | 19 T/m |
| Harmonic Number | 10 |
| RF Frequency | 1.82 ~ 1.87 MHz |
| Average Circulating Beam Current | 9.3 ~ 9.6 A |
| RF Voltage | 300 kV |
| RF Voltage per Cavity | 40 kV (10 kV/gap) |
| The Number of RF Cavities | 8 |
| Beam Emittance at Injection | 54 p mm·mrad |
| Beam Emittance at Extraction | 4.1 p mm·mrad |

**Table 3** Main parameters of the 3-GeV RCS.

| | |
|---|---|
| Energy | 3 GeV |
| Beam Intensity | 8× 1013 ppp |
| Repetition | 25 Hz |
| Average Beam Current | 333 mA |
| Beam Power | 1 MW |
| Circumference | 320 m |
| Magnetic Rigidity | 3.18 ~ 12.76 Tm |
| Lattice Cell Structure | 3-Cell DOFO ¥ 3 module + 1-Straight Cell |
| Typical Tune | (7.35, 7.3) |
| Momentum Compaction Factor | 0.005 (no transition below 6 GeV) |
| Total Number of Cells | 30 |
| The Number of Bending Magnets | 36 (3 m ) |
| Magnetic Field | 0.23 ~ 0.91 T |
| The Number of Quadrupoles | 75 ( 0.75 m, 1 m ) |
| Maximum Field Gradient | 5.2 T/m |
| Harmonic Number | 2 |
| RF Frequency | 1.336 ~ 1.82 MHz |
| Average Circulating Beam Current | 8.6 ~ 11.7 A |
| RF Voltage | 450 kV |
| RF Voltage per Cavity | 42 kV (21 kV/gap) |
| The Number of RF Cavities | 11 |
| Beam Emittance at Injection | 220 p mm·mrad |
| Beam Emittance at Extraction | 54 p mm·mrad |

**Table 3**. The lattice has been designed with the following considerations. First, sufficiently long straight sections are necessary to accommodate an extraction system, an injection system, and RF cavities. Second, the maximum strength of bending magnets should be at most 1 T because of fast ramping. For the same reason, the maximum gradient of quadrupole magnets is 8 T/m at most. Third, the momentum compaction factor is adjusted in order to obtain the transition energy far from the extraction energy.

## 5. Research and Development for the Synchrotrons

The R&D program for the JHF accelerators was formed in order to overcome various difficulties associated with their high-intensity character. The R&D program includes:

1) RF accelerating cavities,
2) 50-GeV synchrotron magnet power supplies,
3) 3-GeV synchrotron magnet power supplies, and
4) ceramics vacuum chamber for the 3-GeV synchrotron.

The RF accelerating system should be in stable operation under extremely heavy beam-loading.

The power supply for the 50-GeV synchrotron is another R&D item, since the reactive (wattless) electric power should be eliminated in order to avoid its harmful noisy effect on any electrical system of the Joint Project, other facilities to be operated in the JAERI Tokai site, and other facilities outside the JAERI site.

Three families of the magnets of the 3-GeV RCS are respectively driven through three resonant networks. Then, a precise amplitude and phase control are necessary in order to operate three systems synchronously. In particular, the phase control is an issue.

The rapid cycle of 25 Hz of the 3-GeV RCS led us to use a ceramics vacuum chamber to avoid any harmful effect of the eddy current otherwise induced. The chamber, on the other hand, should RF-shield the beam current by means of copper strips or copper plating, or other methods. A reliable technique is still hard to establish.

It has been seen that the RCS for the joint project is characterized by the challengingly high energy and rapid cycling even for Phase 1. The rapid acceleration required for this option is very difficult to obtain by using the conventional ferrite-loaded cavities, in particular under heavy beam loading. Although ferrite material has been widely used for proton synchrotrons because of its excellent permeability and tunability, it still suffers from some difficulties.

Magnetic alloys (MAs), for example, FINEMET, appear so promising as to simultaneously solve the above problems [23-25]. We decided to use the MA-loaded cavities for both the RCS and main synchrotron. It is noted that they can be used not only for acceleration, but also for barrier-bucket generation and for second-harmonic cavities. The latter two applications will greatly ease both the space-charge problem and longitudinal instability by improving the bunching factor.

The magnet power supplies of the 50-GeV synchrotron will use insulated gate bipolar transistors (IGBT), the gating time of which is so fast and flexible as to avoid a harmful reactive (wattless) power.

Two prototypes of resonant networks for the 3-GeV rapid-cycling synchrotron have been fabricated and tested. They were successfully used to operate two networks in phase within 1 mrad, which correspond to 0.01 in betatron tune difference.

Some ceramics chambers have been fabricated in order to study the reliability of the materials and the glass brazing. The metalizing and brazing methods are also being investigated.

**6. Conclusion**

We believe that the required specifications can be obtained on the basis of the success of the R&D work, except for the beam-loss problems. Even slight beam losses in this kind of powerful proton accelerators would generate an enormous amount of radioactivity, making impossible the hands-on maintenance of the accelerators, which is a more serious problem than shielding. We are trying to localize any significant beam loss to those places especially designed for this purpose. Since the beam-loss mechanisms have not been fully elucidated, it will be a real challenge in the Joint Project accelerators.

Hoping that we can solve the beam-loss related problems through beam studies and machine improvements, we are seriously considering the possibility of future upgrades of the machines.

## IV. Radiation Safety

The guideline for radiation safety for the Joint Project of the High-Intensity Proton Accelerator Complex is presented. The issues discussed are the bulk shielding and activated soil, cooling water and air.

The bulk shielding is designed so as to satisfy several requirements, such as the dose rate at the surface of the shielding, skyshine at the site boundary, and the activation of soil outside the shielding.

The accelerators of the facility are assumed to be designed and equipped so that the beam loss rate will be less than 1 W/m to permit "hands on maintenance" of the accelerators, at all points except for some limited areas such as injection regions, extraction regions, and so on. Uniform beam loss of the accelerator rings (3 GeV and 50 GeV) is specified as 0.1% of the beam power and this value is also less than 1W/m.

## V. Future Extension of the Project

### 1. Purpose of the Phase 2 Upgrade

The major purpose of the Phase 2 project is to upgrade the accelerator power from 1 MW to 5 MW, so that the neutron scattering project as well as the transmutation project can be made much more powerful. High-intensity neutron beams are the most crucial element in neutron sciences, in particular, in structural biology. The beam power of 5 MW and, hopefully more than 5 MW, is needed for neutron sciences. In addition, it helps to have a high power for R&D of nuclear waste transmutation.

### 2. Accelerators from 1 MW to 5 MW

During the course of the design study of Phase 1, we have been keeping in mind the future upgradability of Phase 1 accelerators to Phase 2. The word upgradability means that most of the accelerator modules built in Phase 1 can be used as part of the upgraded system.

In discussing a possible option for the upgrade of the spallation neutron source it is worthwhile to note the unique position of the Joint Project accelerator complex compared to other pulsed spallation neutron sources. A several-GeV synchrotron is necessary as a booster to the 50-GeV, high-intensity accelerator. Then, the booster can serve as a high-intensity pulsed neutron source as well as a muon source. This is the reason why we chose the rapid-cycling synchrotron (RCS) option for the neutron source. Another option is to choose a combination of a full-energy linac and a storage ring (SR) for the MW pulsed neutron source, examples of which are ESS and SNS. It is controversial which is a better option.

The upgrade path will be chosen on the basis of empirical results obtained through Phase 1. If it turns out that the RCS scheme is more promising than the SR scheme, we will upgrade the Phase 1 RCS to 6 GeV and will build one more 6-GeV RCS in order to provide the 5-MW beam. Each 6-GeV RCS will operate with a repetition rate of 25 Hz, while the target bombarded by the two RCSs will be operated at 50 Hz.

If the result is the opposite, we will upgrade the linac to higher than 1 GeV and will construct two or three SRs. The beam is injected and stored in the first SR, until the injection to the last SR is completed, and then the beams from the two or three SRs will be merged. Either path, RCS or SR, is possible. The upgrade paths conceived in the Joint Project are summarized in **Table 5-1**.

### 3. Particle and Nuclear Physics at Phase 2

For particle and nuclear physics programs at Phase 2, a variety of significant improvements can be expected in conjunction with the upgrade of the 50-GeV PS. Some features considered for Phase 2 are the followings:

1. Use of increased proton intensity
2. Improvement of the duty factor of the proton beam
3. Heavy-ion beams and polarized-proton beam
4. Extension of Experimental Hall
5. New facilities associated with the 50-GeV PS

### 4. Neutron Science at Phase 2

The final goal of the proposed Neutron Scattering Facility is to provide high neutron beam intensity from a 5-MW pulsed spallation source. An upgrade scenario of the neutron scattering facility is considered in the followings.

Target upgrading

A liquid metal target system is absolutely required for a 5 MW beam because a solid target system can not survive the radiation damage for even a month. Our strategy for the development of targets is 1) to confirm the liquid system for 1-MW beam level at phase 1, 2) to accumulate material irradiation data, and 3) to prepare a backup system in case of a fatal problem is found in a liquid metal system design.

Extensibility of the biological shield

The facility at Phase 1 is basically designed assuming the 5 MW operation. However, biological shield of the target station is designed for a 1-MW operation at first phase, because the shielding cost is very expensive and the required shield thickness has some uncertainty. So the shielding performance can be measured at the Phase 1 operation, and a necessary additional shield thickness will be confirmed. The reinforcement will be done at the outside of the shield.

Extension of the experimental hall

For the experimental hall, the building structure is considered to be extensible with increase of the beam line requirement. At the same time, the possibility of second target station will be discussed if a user requirement and scientific importance are strongly increased at that time.

## 5. Muon Science at Phase 2

Installation of the ultra-high intensity $\mu^+/\mu^-$ channel will be mainly considered in the second phase of Muon Science. A high-field focusing superconducting solenoid will be placed adjacent to the pion production target. Such a large-scale installation of a superconducting magnet system will open new fields of Muon Science.

Another new facility is a muon accumulator ring where energetic muons (of a few GeV) produced by the 50-GeV PS are stored, and decays of these muons provide neutrinos of very high intensity. To inject more muons effectively, ionization cooling of muons will be necessary, together with solenoid capture and phase rotation. This muon accumulator ring will also be used to study the muon anomalous magnetic moment (g-2) and the muon electric dipole moment (EDM) which are known to be sensitive to new physics beyond Standard Model. A new-generation experiment after the one at the BNL/AGS can be considered at the 50-GeV PS by using this muon ring. These efforts will also lead to further R&D programs for a muon collider project.

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